2018

Analysis of nasal airway symmetry and pharyngeal airway following rapid maxillary expansion

BOSTON UNIVERSITY

HENRY M. GOLDMAN SCHOOL OF DENTAL MEDICINE

THESIS

ANALYSIS OF NASAL AIRWAY SYMMETRY AND PHARYNGEAL AIRWAY FOLLOWING RAPID MAXILLARY EXPANSION

by

CHARLES JOHN DICOSIMO III

B.A., University of Rochester, 2006
D.M.D., Boston University, 2015

Submitted in partial fulfillment of the requirements for the degree of

Masters of Science in Dentistry
In the Department of Orthodontics and Dentofacial Orthopedics

2018

Approved by

First Reader

Goli Parsi, DMD, DScD, CAGS
Clinical Assistant Professor, Department of Orthodontics & Dentofacial Orthopedics

Second Reader

Melih Motro, DMD, PhD
Clinical Assistant Professor, Department of Orthodontics & Dentofacial Orthopedics

Third Reader

Leslie Will, DMD, MSD
Anthony A. Gianelly Professor and Chair, Department of Orthodontics & Dentofacial Orthopedics
Director, Advanced Specialty Education Program in Orthodontics & Dentofacial Orthopedics Dental Health Center

DEDICATION

I would like to dedicate this work to my parents, my family, and my wife. I would not have been able to get to this point in my life without your constant support, love, and guidance in all that I do. Thank you for always being there for me.

ACKNOWLEDGMENTS

First I would like to thank my research mentor, Dr. Goli Parsi. I appreciate all of the time and effort you put in to help guide me in this project. I am appreciative of all of the hours spent together adjusting and perfecting the methodology in the study as well as the many hours of review of the various research updates and presentations throughout my orthodontic residency program.

Second I would like to thank Dr. Melih Motro for all of his help throughout this research project. I am extremely appreciative of the many hours you spent with me in training on the Mimics software as well as answering my questions along the way. Dr. Parsi and you were a great team and resource for me in completion of this research project.

Finally, I would like to thank Dr. Leslie Will, as well as the entire faculty in the Orthodontic and Dentofacial Orthopedics Program at Boston University. I am thankful to have had such great faculty to support me throughout my orthodontic residency and to allow me to reach my lifelong career goal of becoming an orthodontist.

ANALYSIS OF NASAL AIRWAY SYMMETRY AND PHARYNGEAL AIRWAY FOLLOWING RAPID MAXILLARY EXPANSION

DR. CHARLES JOHN DICOSIMO III

Boston University School of Dental Medicine, 2018

Major Professor: Dr. Goli Parsi, Clinical Assistant Professor, Department of Orthodontics & Dentofacial Orthopedics

ABSTRACT

Objectives: This retrospective cohort study tested the effect of Rapid Maxillary Expansion (RME) on symmetrical volumetric changes in the nasal cavity. Volumetric changes in overall nasal cavity, nasopharynx, and oropharynx were also assessed as well as minimum cross-sectional width changes and molar angulation in association with RME.

Methods: CBCT scans of before and after RME treatment for 28 subjects (17 females, 11 males, average age 9.85 ± 2.42 years) were collected from a previously de-identified database. All subjects were treated for maxillary constriction using banded hyrax expanders. Mimics software was utilized to segment the nasal and pharyngeal airways and create various compartments (left and right nasal cavity, nasopharynx, and oropharynx) for volumetric analysis. Minimum cross-sectional width measurements and maxillary first molar angulation were also assessed. Paired T-test was used to quantify the changes brought about by expansion. Statistical significance was set at the 0.05 level.

Results: Posterior expansion as measured between right and left greater palatine foramen (GPF) averaged 2.41 mm (SD = 1.03 mm). There were statistically significant differences in overall nasal cavity (2249.6 ± 2102.5 mm^3), right nasal cavity (968.8 ± 1082.7), left nasal cavity (1197.3 ± 1587.0), nasopharyngeal (1000.6 ± 917.7), and oropharyngeal (2349.2 ± 2520.8) volumes. In comparing the right to left nasal cavity, no significant changes were noted for initial volume, post-expansion volume, or pre to post-expansion changes (T2-T1). For cross-sectional analysis, the right nasal cavity (0.13 ± 0.07 mm) and left nasal cavity (0.11 ± 0.06 mm) showed significant increases in minimum cross-sectional width measurements. Initial maxillary molar angulation had no significant correlation to initial nasal cavity volume on either side.

Conclusions: RME has significant benefits to increasing nasal and pharyngeal airway cavity volumes in all segments of the airway. Nasal cavity expands symmetrically. Minimum cross-sectional width of the left and right nasal cavities showed highly symmetrical improvements. Initial maxillary molar angulation has no relationship to initial nasal cavity volume.

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LIST OF ABBREVIATIONS

3-D	Three-Dimensional
ANS	Anterior Nasal Spine
C3	Cervical Vertebra #3
CBCT	Cone Beam Computed Tomography
FD	Frankfort Derivative
GPF	Greater Palatine Foramen
HU	Hounsfield Unit
IOF	Infraorbital Foramen
Mid-N	Middle of Nasal Bone
N	Nasion
OSA	Obstructive Sleep Apnea
RME	Rapid Maxillary Expansion
Pir	Piriformis
PNS	Posterior Nasal Spine
ProN	Pronasale
Tip-N	Tip of Nasal Bone

INTRODUCTION

Rapid maxillary expansion (RME) is an orthodontic treatment that dates back to the 1800s. Articles by Timms [1] and Gray [2] allude to the 1860 *Dental Cosmos* article in which E.C. Angell described separation of the maxilla in order to make room for the canines with the appearance of a midline diastema.[3] While these reports were initially controversial, it was the first glimpse into a technique that would eventually gain significant traction. Wertz [4] mentions the referral of the early 1900s by orthodontists and rhinologists as the "maxillary expansion years." Since 1900, many more reports have been published in regards to the dental and medical implications of rapid maxillary expansion and this has been a significant area of interest in these fields even in present day research.

An article by Mutinelli[5] describes RME as a procedure used for midpalatal suture opening by use of fixed orthodontic appliances during growth to increase the transverse width of the maxillary arch. RME is different from slow maxillary expansion in that it usually involves 2 turns per day while slow maxillary expansion involves 1 turn every other day or greater interval.[6]. It is imperative to recognize the medical and dental implications of RME both at an anatomical/physiologic level and the influences on overall health in order to fully grasp the importance of current research involving this technique. Some of the anatomical/physiological changes as stated by Gray [2] include separation of the maxillae at the intermaxillary suture, expansion of the nasal cavity in three dimensions, rotation of the lower portion of the maxilla, flattening of the palatal arch, and straightening of the nasal septum. An article by Ghoneima et al [7] places emphasis on increases in width of all cranial and circummaxillary sutures other than the frontozygomatic, zygomaticomaxillary, and zygomaticotemporal sutures. In addition, Cleall et al [8] speaks about cellular adjustments between the separated maxillae in the intermaxillary suture leading to development of new bone in the void and reformation of a new normal fibrous suture.

The anatomic/physiologic changes caused by RME are multiple and interesting but the overall health implications are even more impressive. McNamara et al [9] mentions several health related issues associated with maxillary restriction. These include occlusal disharmony and esthetics, narrowing of the pharyngeal airway, increased nasal resistance, poor tongue posture creating problems with oral airway, obstructive sleep apnea (OSA), and higher incidence of mouth breathing leading to a higher palatal vault. Tauman [10] elaborates on the severity of OSA in pediatric patients with narrow palates with such negative side effects as behavioral disturbances, attention problems, cardiovascular issues, compromised somatic growth, depression, enuresis, and overall increased health care costs. Furthermore, Gray [2] targets six medical concerns as a reason for RME: poor nasal airway, allergic rhinitis, septal deformities, recurrent ear, nasal and sinus infections, asthma, and prior to nasal septoplasty procedures.

It is clearly apparent that a narrow maxilla carries implications for several health concerns. A pattern of upper airway obstruction is clearly associated with maxillary constriction. The maxilla has a close anatomical relationship with the nasal cavity and airway so that any change to the maxilla will influence the nasal airway. This has been borne out in current research. Moreover, with 3-D cone-beam imaging (CBCT), we can get an accurate representation of various head and neck structures, including volumetric analysis in these areas. [9,11]

Several studies describe the relationship between RME and nasal airway changes. In one study by Cordasco et al[12], RME produced significant increases in nasal floor width and maximum nasal width as well as the total nasal volume. This study focused more on the lower portion of the nasal cavity. However, the procedure was shown to significantly increase the overall nasal dimensions in the lower portion of the nasal cavity (nasal floor width and maximum nasal width). The results also showed equal distribution when comparing anterior and posterior segments. Hershey et al[13] expressed significant decreases of mean nasal resistance at both 0.25 L/s and 0.50 L/s of air flow. Approximately 66% of their subjects also reported that it became easier for them to breathe through the nose about 1 to 2 weeks after beginning expansion. Another interesting result from this study was an increase in nasal cavity width after expansion as well as a further increase 3 months after retention. Another study by Görgülü et al[14] found that in all subjects, nasal cavity volume continuously increased with progression of expansion. This study noted a 12.1% increase in nasal cavity volume during expansion. This result can be attributed to increase in nasal width and decrease in maxillary sinus width. Warren et al[15] reports similar results in his article showing mean nasal cross-sectional area size of 0.29 cm2 ± 0.05 at initial measurement and 0.46 cm2 ± 0.15 one year later in patients receiving rapid maxillary expansion. He also mentioned that nasal cross-sectional area increased 45% after RME. These results were attributed to alterations at the nasal valve area (which they defined as between the upper and lower lateral cartilages and the pyriform aperture, just beyond the anterior ends of the inferior turbinates) and an increase in alar width. Additionally, this study points to increased nasal airway resistance being due to decreased nasal cross-sectional size. Finally, a study produced by Caprioglio et al[16] further reinforces the above by confirming increased total airway volume and oxygen saturation and decreased apnea/hypopnea index following expansion. All three were of statistical significance. This study also evaluated all levels of the airway using CBCT imaging but only saw significant results in the nasal airway.

These studies and many others confirm the close relationship between the maxilla and nasal airway. Expansion of the maxilla using RME has a significantly positive effect on the nasal airway. Not only does nasal airway resistance decrease after RME, but patients receive other benefits as well. Gray[2] found that 87% of subjects changed from mouth to nose breathers, resulting in less snoring throughout the night; 60% of 212 cases reported fewer upper respiratory infections (colds, sore throats and ears); 93% had decrease in allergic reactions, as well as other benefits such as reduction in wheezing, improved wellbeing, improved concentration, and improved confidence. McNamara et al[9] reiterated these positive effects, stating that the improvement of the upper airway is stable in the long term and improves midface structural and functional problems, snoring, oral breathing, and sleep apnea syndrome during childhood. Furthermore, Pirelli et al[17] ascertains that some children with small adenoids and tonsils may not need such procedures as tonsillectomy or adenoidectomy to improve their sleep apnea, but may experience long-term improvement into adulthood from RME.

While it is evident that RME has many beneficial health aspects, and many studies have similar results regarding nasal airway changes due to expansion, many of these studies have focused on the lower portion of the nasal cavity. Grey[2] states the largest expansion occurs at the level of the inferior turbinates but with varying results of expansion superiorly. Görgülü et al[14] meanwhile claimed that the nasal base has greater expansion in the anterior portion of the maxilla than posteriorly. This expansion was also greater inferiorly than superiorly. Additionally, Cordasco et al[12] talks about transverse skeletal changes showing larger gains in the lower portion of the nasal cavities. Furthermore, Bouserhal et al[18] stated that the main results from RME are apparent in the transverse skeletal dimension with less influence on the vertical and sagittal dimensions.

In addition to this focus, there have been different opinions on the impact on the nasal septum after RME. One study by Farronato et al[19] showed straightening of the septum in nearly all subjects (94%). This result was seen in both the middle and lower septal tracts having an overall positive impact on maxillary growth patterns in young children. On the other hand a study by Altug-Atac et al[20] found no positional changes of the septum after RME was completed as measured by the septal angle deviation from the midsagittal plane. These results are distinctly different and bring up an interesting point regarding symmetry in the nasal cavity following rapid maxillary expansion.

It is apparent from the preceding discussion that RME has important health effects and that many studies have been conducted regarding increase in nasal volume/decrease in nasal resistance. However, there is no significant research focusing on the symmetrical differences within the nasal airway after RME.

The goal of the present study was to retrospectively evaluate patient CBCT imaging before and after rapid maxillary expansion with focus on symmetrical differences. More specifically, the present study evaluated volumetric changes in the overall nasal cavity as well as in various segments of the nasal cavity (left and right nasal cavity, nasopharynx, and oropharynx) and changes in the minimum cross-sectional width measurements of the right and left nasal cavity. The maxillary first molar angulation was also be assessed to see if any relationship existed between molar position and the initial volume of the nasal cavities. By evaluating the symmetrical changes after rapid maxillary expansion, it will give us a more detailed look into the specific magnitude and location where these changes occur. It was anticipated that all segments of the airway would benefit from RME procedure and that the right and left nasal cavity would show similar volumetric and cross-sectional increases. CBCT imaging and analysis software was used to gather precise information that had not been a focus of currently available research and may have potential implications as to how we direct treatment, for our patients.

Aim of Study

The aim of the current study was to evaluate the changes in nasal volume symmetry following rapid maxillary expansion using 3-D imaging. Volumetric changes of the left and right nasal cavities, nasopharynx, and oropharynx were evaluated as well as alterations in left and right minimal cross-sectional width measurements. The initial maxillary first molar angulation was also assessed in relation to initial nasal cavity volume.

MATERIALS AND METHODS

This was a retrospective cohort study approved by Boston University Institutional Review Board (IRB# H-34714). 70 cone beam images of patients who underwent RME procedure was screened and 28 subjects were selected for this study out of the CBCT repository of Boston University Department of Orthodontics (H-32515). Subjects consisted of 11 males and 17 females ranging in age from 5-16 years old (average age 9.85 ± 2.42 years). All of these subjects completed treatment involving rapid maxillary expansion (RME) for nasomaxillary constriction. Treatment for these subjects involved maxillary expansion using a banded Hyrax expander cemented to the maxillary first molars. The focus in the current study was on RME due to the sample being treated with RME protocol. The activation protocol followed was 1 turn per day (0.25mm/turn) until over correction was achieved by having the palatal cusp of upper first molars contacting the buccal cusps of lower first molars. The expander was maintained in the mouth for three months post-expansion. Inclusion criteria for the subjects were 1) Diagnostic imaging including initial CBCT and post-expansion CBCT images 2) Non-syndromic patients 3) Non-surgical expansion and 4) Successful maxillary expansion (confirmed by increase in measurement of the greater palatine foramen on the CBCT from initial CBCT to post-expansion CBCT).

Volumetric Analysis

For each subject the same protocol was followed for both the subject's initial and post-expansion scans. CBCTs were exported as DICOM extension (Digital Imaging and

Communication in imaging). CBCTs were imported into Mimics Software Version 20.0 (Materialise, Leuven, Belgium) and processed and segmented by the same operator (CD). CBCT voxel size was 0.3 mm and i-CAT (Imaging Sc. Int., Hatfield, PA, USA) was set at 120 kVp and 5 mA. The objective in using this software was to extract a 3-D model of the airway for volumetric analysis. Several masks were created (Figure 1) using pre-determined and/or custom thresholds based on Hounsfield units (HU) of the CBCT image in the Mimics software (Table 1).

Tissue Type (mask)	**Threshold Value in Hounsfield Units (HU)**
Bone	226 to 3071
Soft Tissue (CT)	-700 to 225
Air	-1024 to -500 (custom)

Table 1. Masks and threshold values.

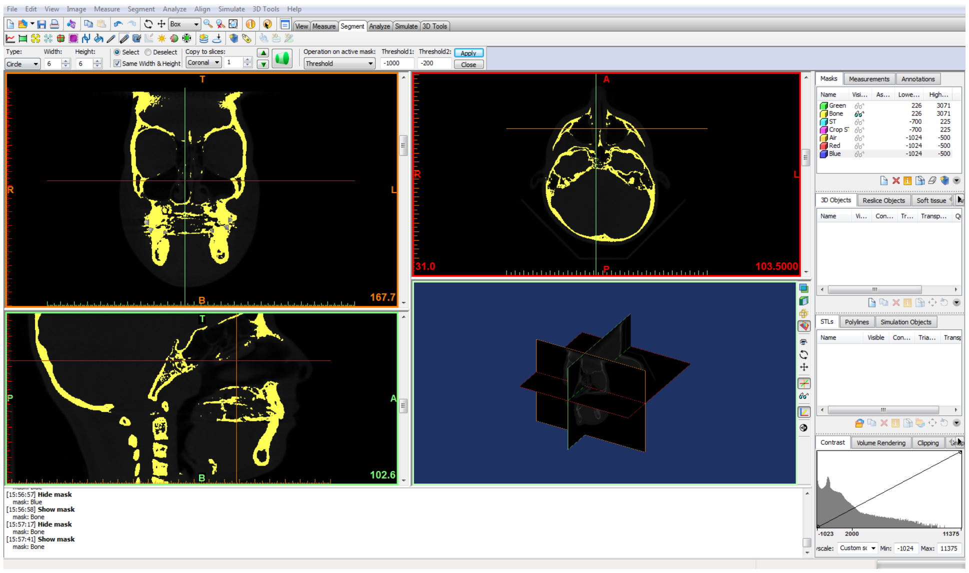

Fig 1a. Bone mask.

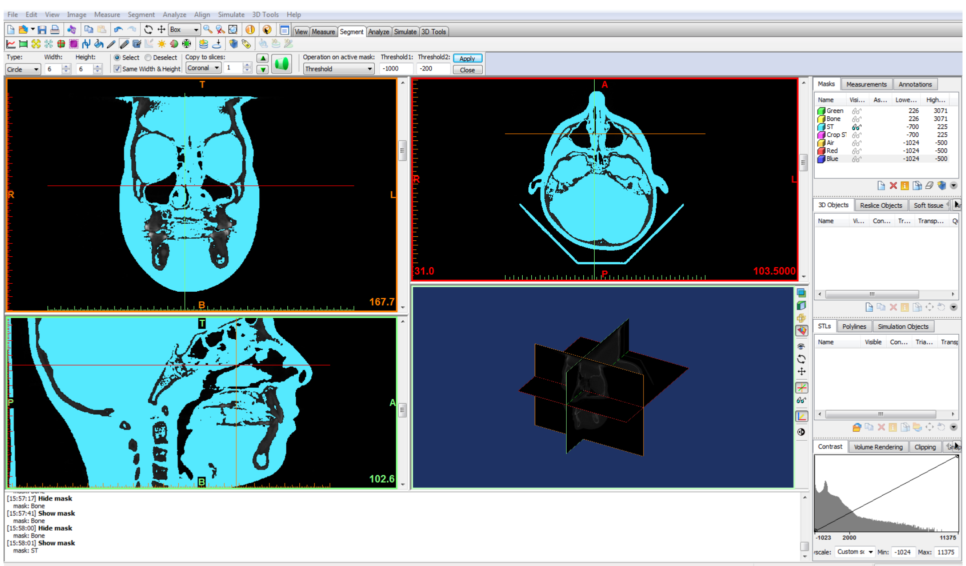

Fig 1b. Soft tissue mask.

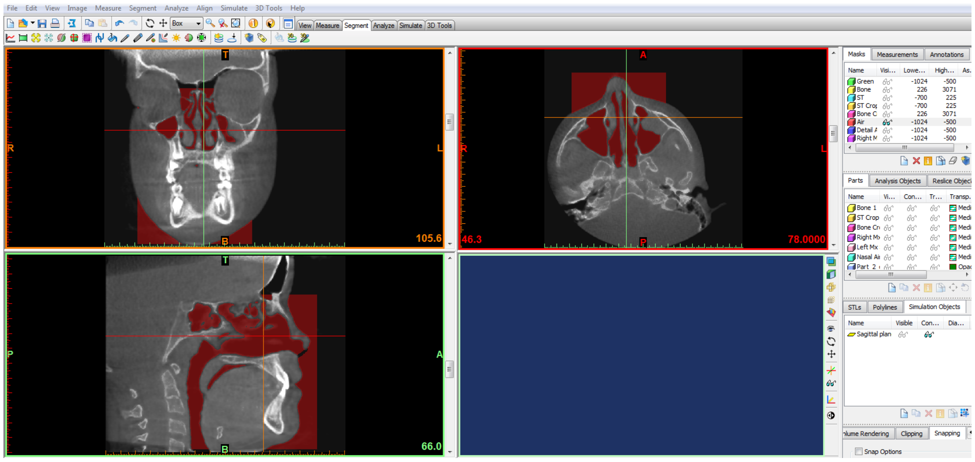

Fig 1c. Air mask.

In addition to creating overall masks for each of these tissue types, each mask was cropped, if necessary, to concentrate on certain areas of the tissue. For instance, a crop of the palate from the bone mask was used to isolate a confined area of the maxilla showing the greater palatine foramina in order to confirm that palatal expansion was successful (Figure 2).

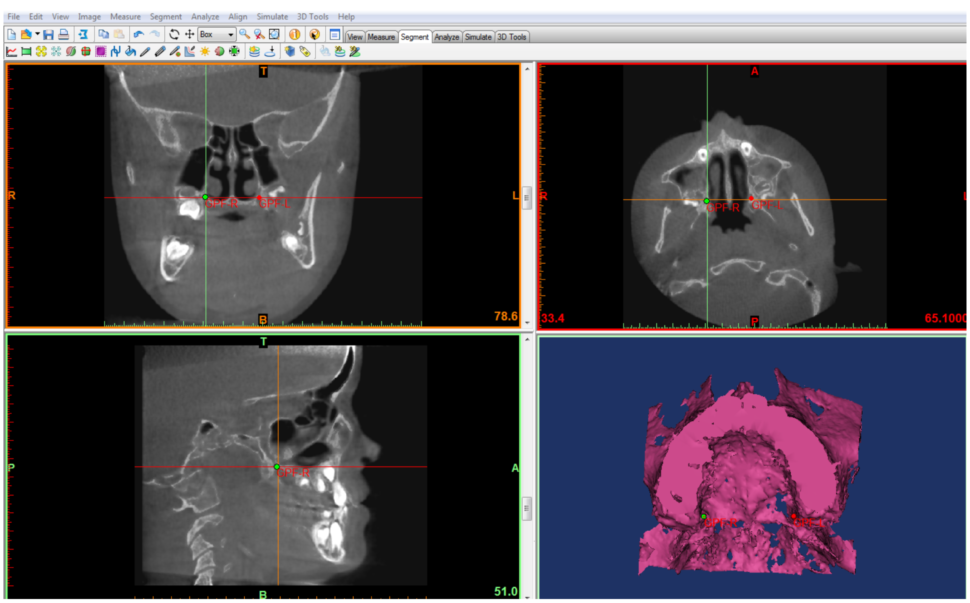

Fig 2. Cropped bone mask showing GPF identification for expansion verification.

The soft tissue mask was cropped to isolate the nose, as the only area of interest was the soft tissue ala and outer border of the nose. The air mask was also cropped to help isolate the internal airway (nasal and pharyngeal) from the air recognized outside of this area of interest.

Following creation of the individual and cropped masks, further segmentation of the air mask took place utilizing the ‘3-D multislice edit’ tool in Mimics software. This tool allowed the researcher to add, remove, and/or threshold areas of the air mask in order to properly segment out the internal airway. Since the custom threshold for air recognized not only the air inside of the skull but also the air outside of the skull, the remove function was used to cut any connection of the inside air to the outside air. In the sagittal slice, lines were manually drawn from subnasale to soft tissue pronasale along the columella. Use of the ‘region-growing’ tool confirmed whether these areas had been separated properly which was indicated by a color change between the outside and inside air. Following separation of the outside and inside air compartments, a new airway mask consisting of solely the inside air was created (Figure 3).

Fig 3a. Cropped air mask containing inside and outside air.

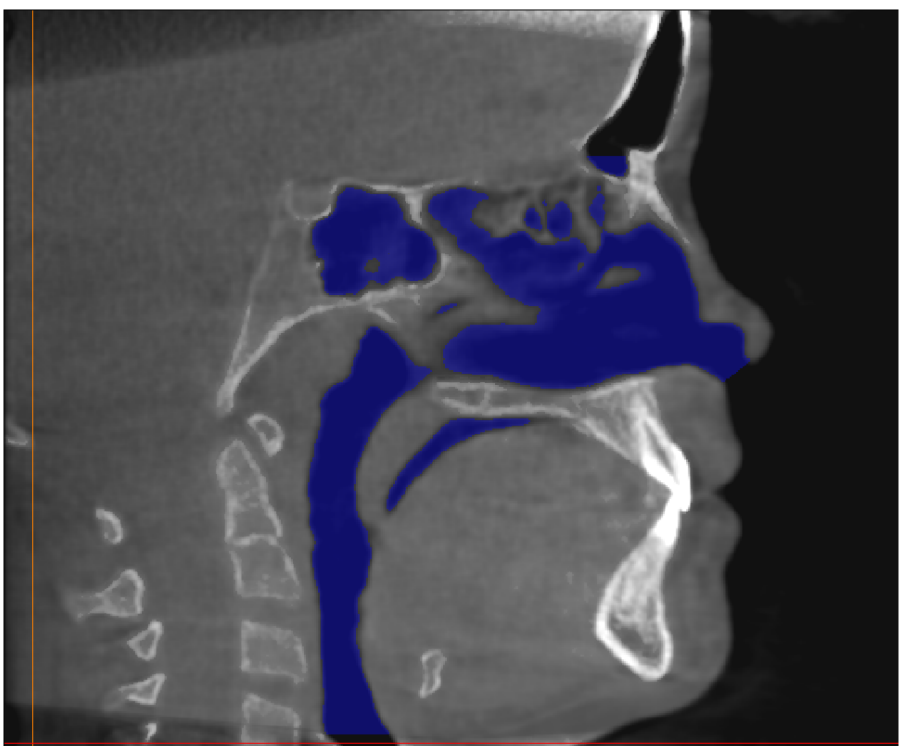

Fig 3b. Air mask following removal of outside air.

This new mask then underwent an additional critical step to fill in areas that were missed by the initial air thresholding value. The '3-D multislice edit' tool thresholding function was used which allowed the researcher to go slice by slice and manually add to areas by changing the initial thresholding value. In order to more properly fill in the airway in areas that were missed initially, the high end of the threshold for this mask was changed from -500 to -400 HUs and colored in manually. This accomplished filling in areas of the airway that were missed without being so low that areas of soft tissue or bone were included (Figure 4).

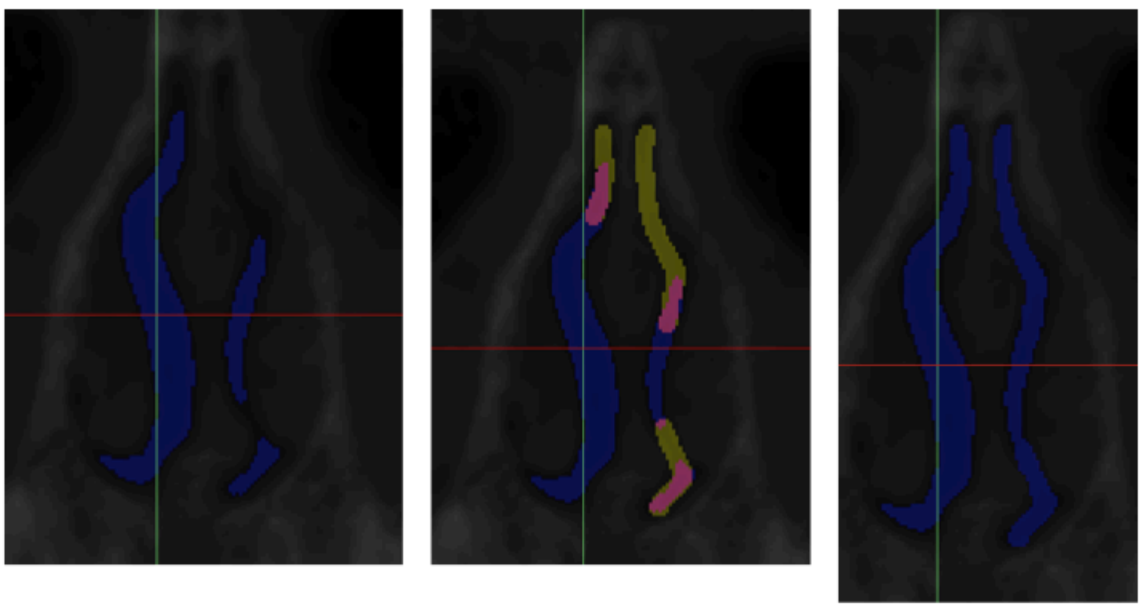

Fig 4. Manually filling in airway where original pre-defined thresholding was not sufficient.

After editing, the paranasal and maxillary sinuses were removed using a combination of the remove function in the '3-D multislice edit' tool, boolean function, and creation of points/planes. By using the remove and boolean functions, any connection to the maxillary sinuses was removed allowing the researcher to separate the nasal airway from the maxillary sinus air cavities (Figure 5).

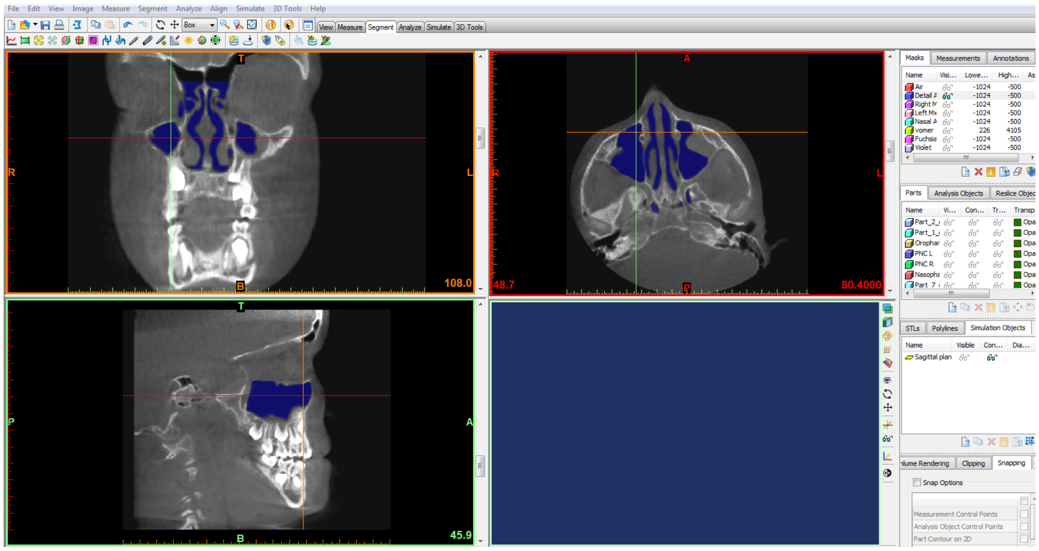

Fig 5a. Airway mask following removal of outside air.

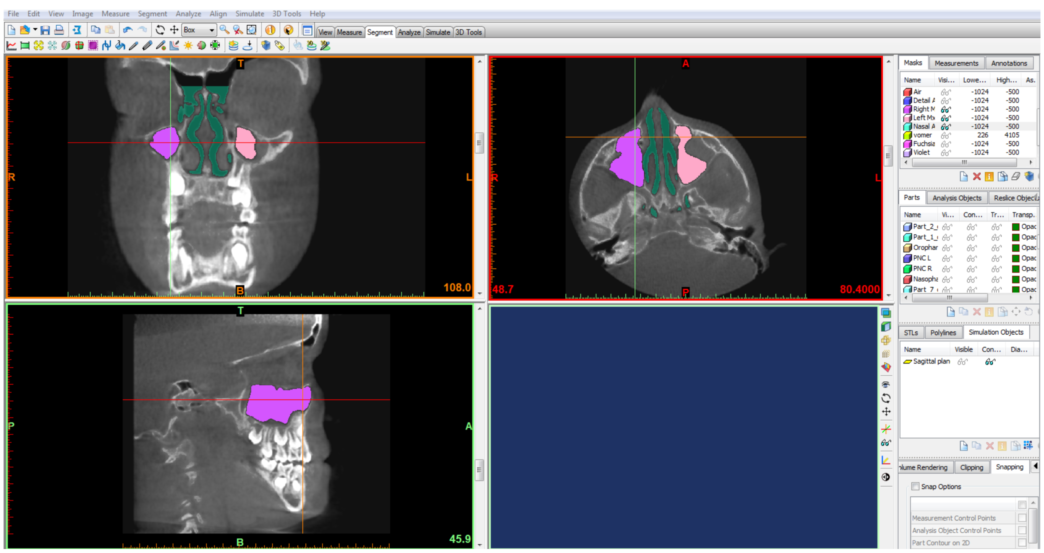

Fig 5b. Segmentation of right (purple) and left (pink) maxillary sinuses.

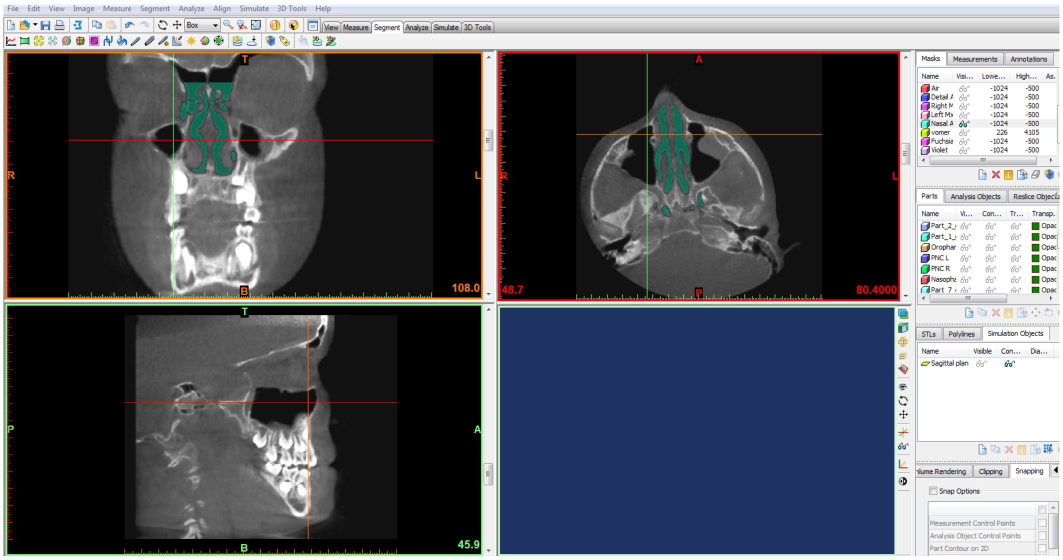

Fig 5c. Use of boolean function to remove left and right maxillary sinuses from original air mask creating new airway mask without the maxillary sinuses.

Points and subsequent planes were established to remove any remaining paranasal air cavities while simultaneously creating differing portions of the airway for analysis (right and left nasal cavity, nasopharynx, and oropharynx). The points, verified on all CBCT slice orientations (coronal, sagittal, and transverse) and subsequent planes (reference and dissector) created from these points for that portion of the segmentation process are listed in Table 2 and Table 3 below. Table 4 describes the borders of the segmented airway cavities. Figure 6 illustrates how the points/planes correspond to the 3-D bone mask.

Point	Description
Anterior Nasal Spine (ANS)	Most anterior and midline point of anterior nasal spine
Posterior Nasal Spine (PNS)	Most posterior and midline portion of palate
Ala Right	Most outside portion of soft tissue ala
Ala Left	Most outside portion of soft tissue ala
C3	Most anterior inferior and medial portion of C3 vertebrae
Greater Palatine Foramen Right (GPF-R)	Most anterior and inferior portion of greater palatine foramen
Greater Palatine Foramen Left (GPF-L)	Most anterior and inferior portion of greater palatine foramen
Infraorbital Foramen Right (IOF-R)	Inferior and mid infraorbital foramen
Infraorbital Foramen Left (IOF-L)	Inferior and mid infraorbital foramen
Mid-Nasal Bone (Mid-N)	Midway between nasion and nasal tip using “measure over surface” function in Mimics
Nasion (N)	Intersection of nasal and frontal suture at its midpoint
Aperture Piriformis Right (Pir R)	Widest portion of aperture piriformis
Aperture Piriformis Left (Pir L)	Widest portion of aperture piriformis
Pronasale (ProN)	Middle most tip of soft tissue of nose
Nasal Tip (Tip N)	Tip of nasal bone
Zygomaticotemporal Suture Superior Right	Most superior portion of suture
Zygomaticotemporal Suture Superior Left	Most superior portion of suture
Zygomaticotemporal Suture Inferior Right	Most inferior portion of suture

Table 2. Description of points used for airway segmentation.

Reference Planes	Description
Frankfort Derivative (FD)	Infraorbital foramen left and right to zygomaticotemporal suture inferior right
Vertical Nasal Plane	Nasion to widest area of right and left aperture piriformis
Dissector Planes	**Description**
Superior border	Midnasal point to right and left zygomaticotemporal suture superior
PNS Plane (inferior border)	Plane through PNS point parallel to FD
PNS Vertical Plane	Plane through PNS parallel to Vertical Nasal Plane
Pronasale Plane	Pronasale to right and left ala
C3 Plane	Plane through C3 point parallel to FD

Table 3. Description of planes used for airway segmentation.

Segment	Borders of Cavity
Right Nasal Cavity	Pronasale Plane to PNS Vertical Plane
Left Nasal Cavity	Pronasale Plane to PNS Vertical Plane
Nasopharynx	PNS Vertical Plane to PNS Plane (inferior border)
Oropharynx	PNS Plane (inferior border) to C3 plane

Table 4. Borders of segmented airway cavities.

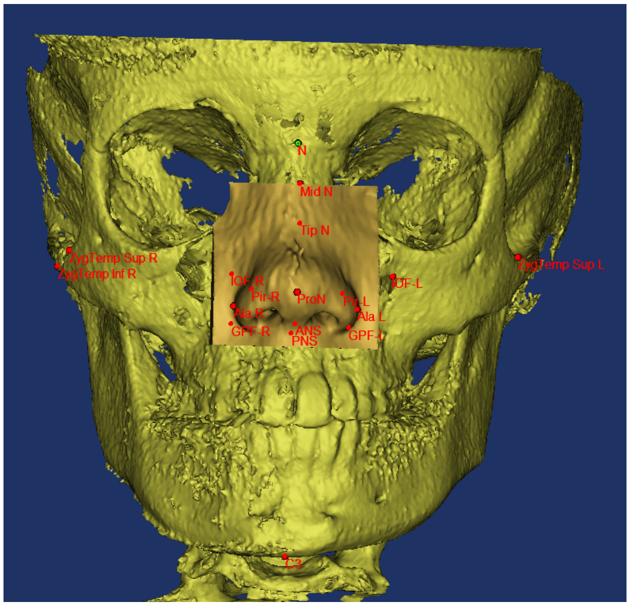

Fig 6a. Points on 3-D bone and cropped 3-D soft tissue mask.

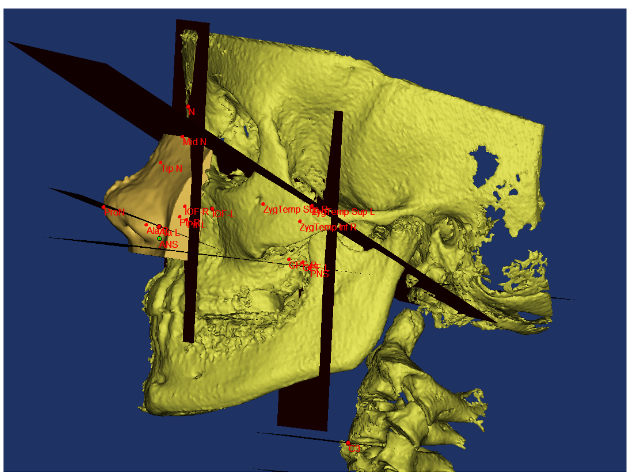

Fig 6b. Planes on 3-D bone and cropped 3-D soft-tissue mask.

Following completion of this segmentation process, a 3-D model of the nasal and pharyngeal airway was extracted using the ‘calculate 3-D’ function in Mimics (Figure 7). In some scans air in the oral cavity between the tongue and the roof of the mouth showed up extending from the oropharynx area. This was removed manually using the ‘3-D multislice edit' tool remove function by cutting the connection of this air space where it attached to the oropharynx.

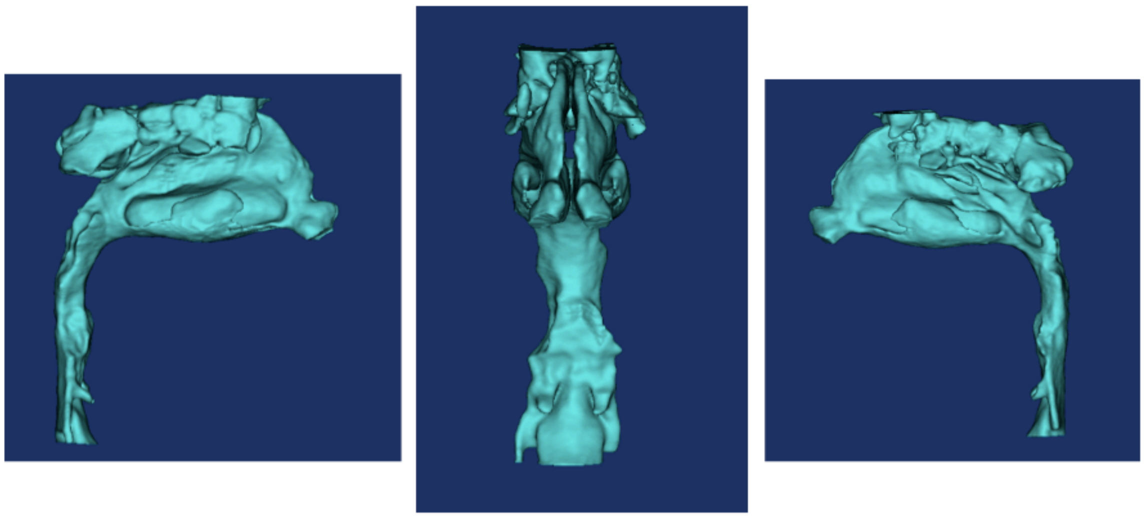

Fig 7. 3-D airway model.

After extraction of this 3-D model the dissector planes mentioned above functioned to slice the airway into various compartments for analysis by using the Mimics cut with polyplane function and split functions (Figure 8).

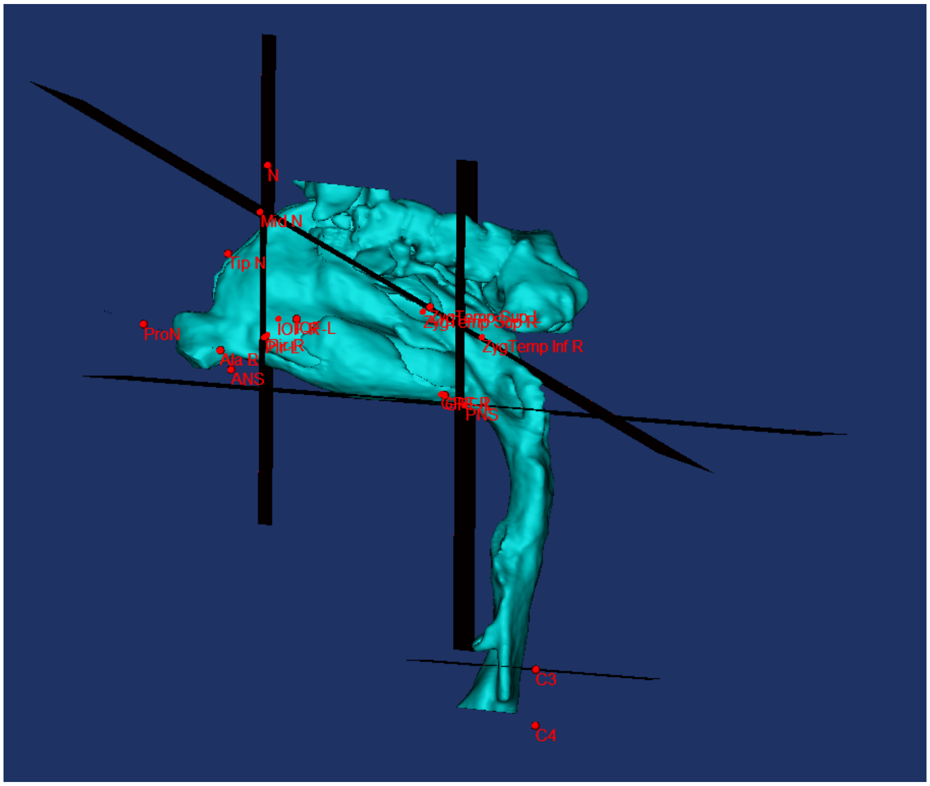

Fig 8. Planes on 3-D airway model some of which were utilized to segment the airway.

These planes created a right and left nasal cavity, nasopharynx, and oropharynx for analysis. Verification of creation of these compartments came from Mimics software assigning different colors to these regions (Figure 9).

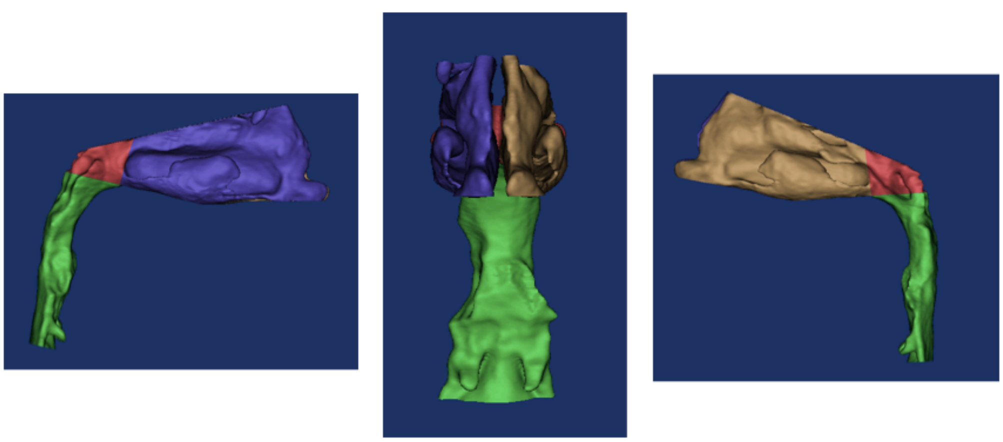

Fig 9. Creation of segments in the airway by cutting with planes.

Each compartment was highlighted in a different color and labeled appropriately. Overall volume and volume change for each of these segments in the airway was then determined and recorded (Figure 10).

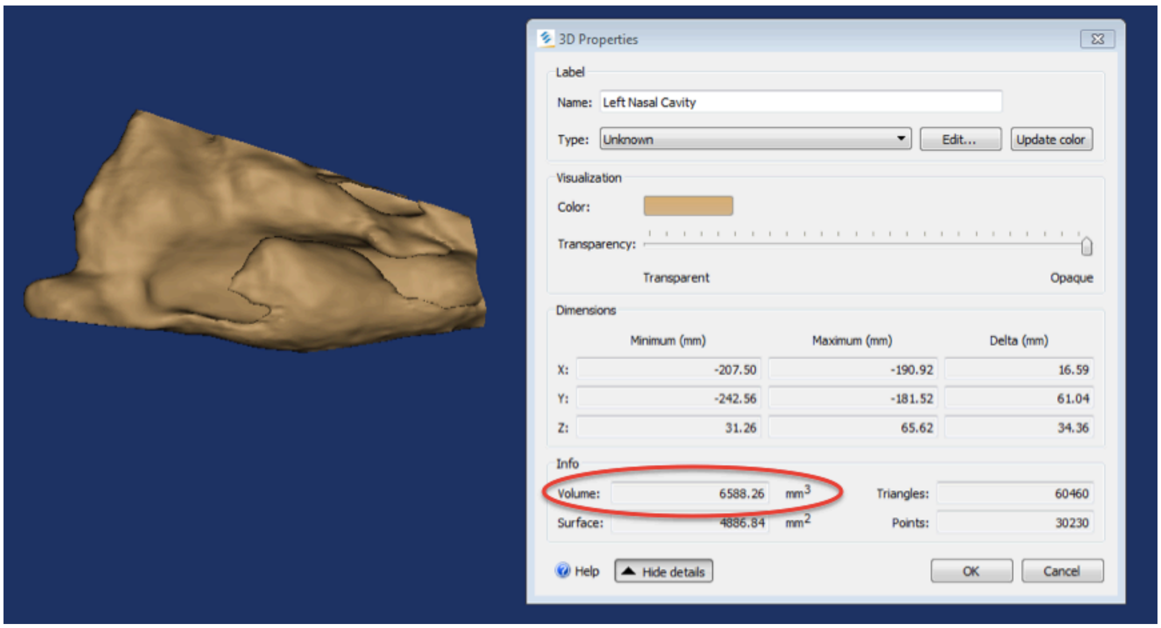

Fig 10. Example of volumetric analysis (Left nasal cavity shown above).

Minimum Cross-Sectional Width Measurements

In addition to volumetric analysis, a methodology for minimum cross-sectional width measurements was developed. This was also completed with the pre and post-expansion scans in Mimics software. Pre-expansion scans were inspected visually until the narrowest portion of the left and right nasal airway was confirmed in the coronal plane. The number of slices from the point pronasale (ProN) was recorded in order to be applied to the post-expansion scan. The narrowest portion of the right and left side of the nasal cavity was then measured using the ruler tool in Mimics software. To be accurate only the least dense areas of the airway (-1000 to -575 HUs) were measured taking special care not to incorporate any of the borders of the airway (bone/soft-tissue). The analogous slices in the post-expansion scans were then identified from point pronasale and the measurements were repeated (Figure 11). Regions were also defined in a superior-inferior direction in order to determine the location of the narrowest portion of the left and right nasal cavity vertically. These regions were from nasal floor to start of middle turbinate, start of middle turbinate to start of superior turbinate, and start of superior turbinate to nasion.

Fig 11. Example of ruler measurement for minimum cross-sectional width.

Maxillary Molar Angulation

Maxillary molar angulation was also measured on the initial CBCT scans utilizing the same methodology as Miner et al.[21] The long axes of the maxillary first molars and a functional occlusal plane line were manually drawn on the initial CBCT scans using the ruler tool in Mimics. The angles between the long axis lines of the upper right and upper left first molars and the functional occlusal plane line were determined using the angle tool in Mimics and recorded (Figure 12).

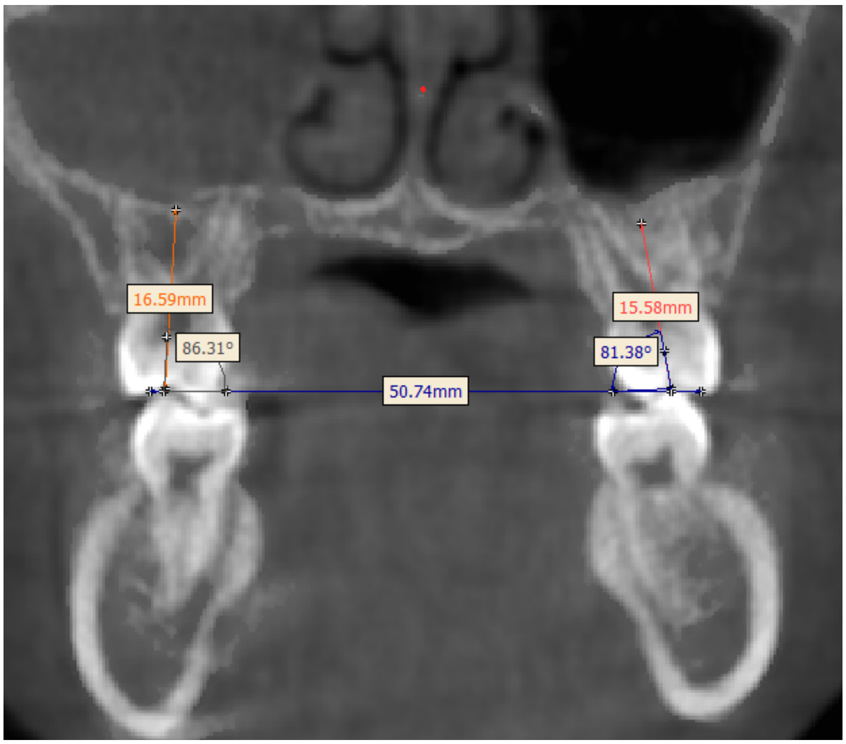

Fig 12. Maxillary Molar Angulation Measurements.

Approximately 10% of the overall sample was re-tested for reliability. All landmarks were digitized by the same examiner (CD) approximately 1 month after initial placement. Intraclass correlation coefficient (ICC) test was run for these variables and reliability was >0.90 for all measurements suggesting landmark placement was highly reliable.

Paired t-tests were used to compare the initial (T1) and post-expansion (T2) volumetric and minimum cross-section width changes following RME procedure, as well as the initial left and right molar angulation differences before RME treatment. Pearson

Correlation test was utilized to test the relationship between initial molar angulation and initial nasal cavity volume. All statistical analysis was completed using SAS Software Version 9.4 (SAS institute Inc., Cary, NC, USA). Statistical significance was set at the 0.05 level

RESULTS

Posterior expansion was measured using the cropped bone mask of the maxilla. The landmarks used were left and right greater palatine foramen. The mean change in linear measurement from initial to post-expansion for these landmarks was 2.41 mm (SD = 1.03 mm, range: 0.96-5.11 mm) and was statistically significant (p value < 0.0001), verifying successful skeletal expansion from the rapid maxillary expansion procedure. Within the 28-subject sample 3 subjects had bilateral crossbite, 4 had unilateral right crossbite, 4 had unilateral left crossbite, and 17 had no dental crossbite at the start of treatment. Crossbite was defined as 2 or more maxillary teeth in edge-to-edge or further positioning with the mandibular teeth.

Volumetric Analysis

Volumetric data was collected from Mimics using the 3-D segmented airway.

The average time interval between initial scan and the next available scan post expansion was 2.07 years (SD = 0.90, range 0.67-4.29 years). Results from this study show that there were statistically significant mean increases in volume in all areas of the nasal and pharyngeal airways. Statistically significant improvements were noted for the overall nasal cavity, right nasal cavity, left nasal cavity, nasopharyngeal cavity, and oropharyngeal cavity (Table 5).

Volumetric Variable	T1 mean ± SD (mm^3)	T2 mean ± SD (mm^3)	T2-T1 mean ± SD (mm^3)	95% C.I. (mm^3)	P-value
Overall Nasal Cavity	7971.6 ± 1801	10082.90 ± 2551.73	2249.6 ± 2102.5	1361.8 – 3137.4	<0.0001
Right Nasal Cavity	4094.90 ± 1079.66	5063 ± 1323.3	968.8 ± 1082.7	549 – 1388.6	<0.0001
Left Nasal Cavity	3813.10 ± 1138.28	4970.3 ± 1564.43	1197.3 ± 1587	569.5 – 1825.1	0.0006
Nasopharynx	2815.88 ± 1037.34	3816.44 ± 1053.21	1000.6 ± 917.7	629.9 – 1371.2	<0.0001
Oropharynx	7645.22 ± 2311.72	9994.40 ± 3511.89	2349.2 ± 2520.8	1308.6 – 3389.7	<0.0001

Table 5. Volumetric analysis before (T1) and after (T2) RME.

Volumetric changes were also grouped according to percent increase in volume following rapid maxillary expansion procedure (Table 6). The greatest percent change in volume on average occurred in the nasopharynx followed by oropharynx, left nasal cavity, and finally right nasal cavity. The overall nasal cavity increased by a mean of 30.82%. While all areas of the nasal cavity and pharyngeal airway increased in volume, these results suggest that for the nasal cavity, the left nasal cavity showed greater mean increase following RME than the right side nasal cavity by 12.29%.

Volumetric Variable	Mean % Change
Overall Nasal Cavity	30.82
Right Nasal Cavity	26.53
Left Nasal Cavity	38.82
Nasopharynx	43.92
Oropharynx	33.76

Table 6. Percent change in volume for segments of airway.

Volumetric analysis was also completed on the nasal cavity alone looking at any statistically significant right-left differences in initial volume or post-expansion volume, and changes in volume (T2-T1) of the right versus the left nasal cavity (Table 7). Results show that there was no statistically significant difference between the right and left initial nasal cavity volumes, right and left post-expansion volumes, or the changes that occurred from pre to post-expansion (T2-T1).

Volumetric Variable	**Mean Difference Left to Right Side (mm^3)**	**95% C.I. (mm^3)**	**P-value**
Initial Nasal Cavity	-281.8	-763 - 200	0.24
Post-Expansion Nasal Cavity	-71.57	-688.1 – 544.9	0.81
T2-T1 Nasal Cavity	-242	-967 – 483.1	0.49

Table 7. Initial, final, and overall change comparison for right and left nasal cavity volumetric analysis.

Minimum Cross-Sectional Width Analysis

For minimum cross-sectional width measurement, both the right and left nasal cavity showed similar areas of most constriction in the coronal plane. This was consistently located it the level of the middle turbinate for all but one subject which was at the superior portion of the inferior turbinate. While the improvement in minimum cross-sectional width was small, the measurements showed highly symmetrical and statistically significant improvements following RME of 0.13 mm and 0.11 mm for right and left side respectively (Table 8).

Cross-Section Variable	T1 mean ± SD (mm)	T2 mean ± SD (mm)	T2-T1 mean ± SD (mm)	95% C.I. (mm)	P-value
Cross-Sectional Width Right	0.34 ± 0.09	0.47 ± 0.12	0.13 ± 0.07	0.10 – 0.16	<0.0001
Cross-Sectional Width Left	0.33 ± 0.08	0.45 ± 0.11	0.11 ± 0.06	0.09 – 0.14	<0.0001

Table 8. Minimum cross-sectional width measurement before (T1) and after (T2) RME.

Maxillary Molar Angulation

Measurements for the pre-treatment maxillary first molar angulation in the coronal plane (long axis to functional occlusal plane) and crossbite were also collected (Table 9). Maxillary right molar angulation averaged 79.7 degrees (SD = 3.98, Range: 73.4-86.6) while maxillary left molar angulation averaged 77.4 degrees (SD = 4.41, Range: 68.4-84.3). There was a statistically significant difference in molar angulation between the right and left maxillary molar angulation (Table 10). Pearson Correlation Test was also run to see if any relationship between initial maxillary molar angulation and initial nasal cavity volume existed. The results of this test showed that no statistically significant relationship exists between these two variables (Table 11).

Subject I.D.	Maxillary Right Molar Angle	Maxillary Left Molar Angle	Crossbite Right (0 = no, 1 = yes)	Crossbite Left (0 = no, 1 = yes)
2	73.5	78.4	0	0
3	73.4	72.2	0	0
7	86.3	81.4	0	0
8	74	73.4	0	0
9	77.8	82.1	1	0
10	74.7	68.4	0	0
11	76.7	79	0	1
17	83.5	80.5	0	1
18	82	79.4	1	1
19	84	76	1	1
24	79.5	73.4	1	1
26	82.8	73.4	1	0
27	84	84.2	0	0
28	86.6	76	0	0
30	76.3	69.4	0	0
33	81.2	73.8	0	0
39	83.1	72.3	0	0
40	83.1	82.5	1	0
44	80.1	77	0	0
46	83.7	83.3	1	0
48	78	80.1	0	0
54	74	75.2	0	0
56	78.6	80.6	0	0
58	74.4	76	0	0
59	80.8	84.3	0	0
60	81.5	81.2	0	0
61	79.3	75.1	0	0
62	79.7	79.3	0	1

Table 9. Maxillary molar angle and crossbite analysis.

Variable	Mean (Degrees)	SD (Degrees)	Min (Degrees)	Max (Degrees)	P-Value
Maxillary Right 1st Molar Angle	79.7	3.98	73.4	86.6	NA
Maxillary Left 1st Molar Angle	77.4	4.40	68.4	84.3	NA
Maxillary Right to Left Molar Angle Comparison	2.28	4.54	-4.90	10.76	0.01

Table 10. Maxillary molar angle analysis and comparison.

	Maxillary Right Angle	Maxillary Left Angle	Right Nasal Cavity Initial Volume	Left Nasal Cavity Initial Volume
Maxillary Right Angle	1.00000	0.41623 0.0276	0.06143 0.7562	0.15498 0.4310
Maxillary Left Angle	0.41623 0.0276	1.00000	0.22048 0.2596	0.31790 0.09992
Right Nasal Cavity Initial Volume	0.06143 0.7562	0.22048 0.2596	1.00000	0.37321 0.0504
Left Nasal Cavity Initial Volume	0.15498 0.4310	0.31790 0.0992	0.37321 0.0504	1.00000

Table 11. Pearson Correlation Coefficient table for relationship between initial maxillary molar angulation and initial nasal cavity volume.

DISCUSSION

Rapid maxillary expansion has long been employed by orthodontists. It has been extensively studied by both orthodontists and physicians due to its broad benefits to patients, especially those with nasomaxillary constriction. It was the author's intent to build upon prior research on rapid maxillary expansion and nasal/pharyngeal airway changes and examine the specific 3-D anatomic changes that accompany expansion as well as the symmetry of the changes. Evaluation of molar angulation and its correlation to initial nasal cavity volume was also undertaken in this study.

While prior research has been dedicated to maxillary expansion and accompanying changes in the nasal cavity, nasopharynx, and oropharynx, [9,11,14] it was the author's intent to split the nasal cavity into left and right segments to see if the benefits of expansion are symmetrical. This has a high clinical relevance because patients may present with significant anatomical variability, especially in such a complex structure as the nasal airway.

Volumetric analysis results in this study showed that all areas of the nasal cavity and pharyngeal airways significantly improved following rapid maxillary expansion. The overall nasal cavity showed an average increase of 2249.6 ± 2102.5 mm^3 (by 30.82%). One study by Görgülü et al[14] found smaller average increases in overall nasal cavity volume compared to this study. They utilized a 2-turns/day activation protocol but did not include the total number of turns or total amount of skeletal expansion achieved. They also had a shorter time span between scans (6 months post-expansion) and an older mean subject age (13.86 years), which may help to explain the lesser average nasal cavity volume changes. A second study by Smith et al[22] found larger average increases in overall nasal cavity volume than our study. This study utilized a 4-turns/day activation protocol, older mean age (12.3 years), and post-expansion scans 3 months after completion of expansion. These factors and possible difference between the amount of total expansion achieved in our study and Smith et al.'s [22] protocol which was not included may explain the disparity in the amount of volume change. Additionally, a study by Caprioglio et al[16] found similar average nasal cavity volume increase following RME as our study. Their activation protocol was 1-turn/day for an average of 32 days yielding about 8 mm of expansion at the level of the teeth. They had a slightly younger average age (7.1 years) subject population, and a long time span between pre and post-expansion scans (12 months post-insertion). This protocol more closely aligns with our study's methodology although the amount of true skeletal expansion is not reported.

As for the nasopharyngeal and oropharyngeal cavities, our study found increases of 2815.66 mm^3 and 7645.22 mm^3 respectively. Our results found significantly higher increases in the volume of these compartments of the airway in comparison to other similar literature.[22,23] This may be due to differences in landmarks and planes used to define these airway compartments. Another possibility is our subjects may have changed their tongue posture after RME more than in other studies. Iwasaki et al[24] found that following RME the intraoral volume was reduced, the total pharyngeal volume was increased, and the retropalatal volume was increased due to change from low to high tongue posture. It is a difficult task to find a study with the same or even similar landmarks, planes, and technique for compartmentalization of the airway, as there are many ways to complete this task. Overall, it is an encouraging trend to see increases in these segments of the airway following RME which was also the trend seen in our study.

Additionally, our study looked at the left and right nasal cavity volume changes following RME. No other study could be found in the literature analyzing the symmetry of the nasal cavity following maxillary expansion procedure. The results of our study found an average increase of 968.8 mm^3 in the right nasal cavity and 1197.3 mm^3 in the left nasal cavity. This corresponded to a 26.53% average increase in volume in the right nasal cavity and a 38.82% average increase in volume in the left nasal cavity. While this seems like a significant difference, t-test comparison of left and right nasal cavity found no significant differences in initial volume, post-expansion volume, or the changes that occur from pre to post-expansion (T2-T1). This revealed that even though there appears to be an asymmetry in volume change in terms of percent increase, this percent increase in not enough to be statistically significant from left to right side. In other words, the expansion of the left and right nasal cavity does not show any statistically significant difference to one another before, after or throughout the expansion procedure. Results from this study lead us to believe that expansion is symmetrical and benefits the right and left nasal cavity, nasophrynx, and oropharynx. Future data collection with a larger sample size would be required to see if the same trend continues.

In conducting 3-D analysis of the airway following RME, there are a few other factors in terms of methodology that the author would like to point out in comparison to other similar literature. In studying the effects of palatal expansion, it is imperative to identify that true skeletal expansion has occurred. We intended to find a reliable and reproducible landmark to expansion had taken place. In previous studies, it appears that many methods and landmark techniques have been used to verify expansion has occurred. There is use of skeletal landmarks near dental reference points[25], only skeletal[23,26], or a combination of dental and skeletal.[27,28] Expanders come in many varieties, most of which are tooth borne, although in recent years bone borne expanders are increasingly used. Research is available comparing and contrasting tooth borne and bone borne expanders and their side effects.[29] In this study and many previous ones, the expanders used were tooth-borne. It is a risk to use dental landmarks as a confirmation of skeletal expansion because a side effect of tooth borne expanders is dental tipping.[29,30] By using a skeletal landmark, such as greater palatine foramen in this study, we can use a skeletal landmark to confirm expansion has occurred.

It should be noted that there might be differences between this study and others in the literature in terms of the airway segmentation process. It was noted previously that in using Mimics software's predetermined thresholding values, some areas of the airway were not highlighted based on the Hounsfield units (HUs) of the threshold in the program. It was necessary for the author to manually fill in these areas slice by slice. While significant care was taken not to highlight any bone or soft tissue, it is a potential source of error when collecting volumetric data if areas were either missed or overfilled. Several similar studies have been conducted in which 3-D imaging and software was used to gather volumetric data on the nasal and oropharyngeal airway spaces. Many of these studies give great detail about the segmentation points/planes used but do not go into any significant methodology on how the areas of interest were highlighted or filled in for future 3-D volumetric analysis before the segmentation takes place.[11,31,32]

Finally, the author would like to point out potential limitations in this study. These include growth, visual identification of narrowest portion of the nasal cavity, variability in patient factors during CBCT capture, and use of Hounsfield units (HUs) on CBCT scans for analysis.

Our first limitation is growth. As orthodontic clinicians, we are consistently applying treatment to growing patients. This study had an average age of 9.85 ± 2.42 years. Rapid maxillary expansion also typically takes place before the midpalatal suture has fused so therefore, usually takes place on growing patients. This study did not incorporate an age-matched control group. The time difference between initial and post-expansion scans averaged 2.07 years. There is a high likelihood that some of the volume increase noted in this study could be attributed to growth of the patient over this time span. It is the author's intent to analyze an age-matched group of untreated children to determine the effects of growth. Some studies found in the literature utilized a control sample[27] and many others that have not. [11,14,22,23,25,26,28,31,32] Many of the studies that did not incorporate the control group had shorter time spans between initial and post-expansion scans than the current study. This is certainly a potential source of error. It is beneficial to be able to have a matched control sample as a means for comparison or take CBCTs immediately before and immediately after expansion to minimize error due to growth.

Our second limitation is visual identification of minimum cross-sectional measurements. Mimics software was not able to identify minimum cross-sectional area of each segment of the airway and this had to be assessed visually. There could certainly be some error in identifying the narrowest portion of the airway in the coronal plane visually. As technology improves, the author is hopeful that minimum cross-sectional area of a 3-D model can be accurately identified which may be of great value to clinicians in pinpointing the areas of most concern.

Our third limitation is the variability in patient factors during CBCT capture. Several factors can alter the quality of a CBCT scan and affect the airway space. Two major factors are motion due to swallowing or breathing and tongue position.[33–35] While the author of this study made special care to find scans of good quality for analysis, there was no way to confirm if a standard method was used during capture of the CBCT image. In other words, we could not confirm if all patients used a standard breathing or tongue position protocol during image capture.

Finally, a fourth limitation of this study involved the use of Hounsfield Units (HUs) on CBCTs for analysis. CBCT is usually preferable to CT scans due to the lower radiation, shorter acquisition time, more affordable machines, and submillimeter resolution.[36] However, in a CT scan, Hounsfield Unit (HU) is proportional to the degree of x-ray attenuation by the tissue but in a CBCT scan the degree of attenuation is based on grey-scale (voxel value).[36] Furthermore, although CBCT manufacturers and software providers present grey scale as HUs, these measurements are not true HUs.[36] In our study we applied masks of different tissues in HUs on a CBCT. This could be a potential source of error when determining exact volumes of the airway if these units of measure are not as accurate on a CBCT.

Overall, the author tried to analyze scans of pre and post-expansion with special emphasis on symmetrical differences in nasal cavity volume and minimum cross-sectional width. Future analysis with a larger sample size and age-matched control group would help to confirm the results found in this study. It is the author's hopes that rapid maxillary expansion, a vastly studied procedure for over one hundred years, continues to be examined and improved in ways that can both benefit the clinician and the care provided to their patients.

CONCLUSIONS

Results of this study suggest that rapid maxillary expansion has significant benefits to increasing nasal and pharyngeal airway cavity volumes in all segments of the airway. All portions of the airway as defined in this study showed highly significant increases in volume from initial scan to post-expansion scan including right nasal cavity, left nasal cavity, nasopharynx, and oropharynx. In looking more closely at the nasal cavity, the left nasal cavity showed more improvement than the right nasal cavity by 12.29%. While this seems to show asymmetry between the left and right nasal cavity, this percent difference was not statistically significant, suggesting symmetry in expansion. Additionally, cross-sectional width measurements showed highly symmetrical increases between right and left nasal cavity in the coronal plane. Maxillary molar angulation had statistically significant differences from left to right first molar angulation but did not show any statistically significant relationship to initial nasal cavity volume. Overall, the results of this study are highly encouraging and re-establish that rapid maxillary expansion can be a helpful procedure to patients with nasomaxillary constriction regardless of the location of the constriction. These results highlight the need to properly diagnose patients with nasomaxillary constriction and provide RME treatment to help improve the volume and minimum cross-section of their airway as soon as it is diagnosed. Orthodontists, in conjunction with other healthcare professionals, can help to drastically improve patient's lives with maxillary constriction and help reduce and/or eliminate the associated side effects.

BIBLIOGRAPHY

1. Timms DJ. The dawn of rapid maxillary expansion. *Angle Orthod.* July 2009. http://www.angle.org/doi/10.1043/0003-3219(1999)069%3C0247:TDORME%3E2.3.CO;2?url_ver=Z39.88-2003&rfr_id=ori:rid:crossref.org&rfr_dat=cr_pub%3Dpubmed. Accessed November 1, 2015.

2. Gray LP. Results of 310 cases of rapid maxillary expansion selected for medical reasons. *J Laryngol Otol*. 1975;89(06):601-614. doi:10.1017/S0022215100080804

3. Angell E. Treatment of irregularity of the permanent or adult teeth. *Dent Cosm*. 1860;1:540-544, 599-600.

4. Wertz RA. Skeletal and dental changes accompanying rapid midpalatal suture opening. *Am J Orthod*. 1970;58(1):41-66. doi:10.1016/0002-9416(70)90127-2

5. Mutinelli S, Cozzani M. Rapid maxillary expansion in contemporary orthodontic literature. *APOS Trends Orthod*. 2016;6(3):129. doi:10.4103/2321-1407.183148

6. Huynh T, Kennedy DB, Joondeph DR, Bollen A-M. Treatment response and stability of slow maxillary expansion using Haas, hyrax, and quad-helix appliances: A retrospective study. *Am J Orthod Dentofac Orthop*. 2009;136(3):331-339. doi:10.1016/j.ajodo.2007.08.026

7. Ghoneima A, Abdel-Fattah E, Hartsfield J, El-Bedwehi A, Kamel A, Kula K. Effects of rapid maxillary expansion on the cranial and circummaxillary sutures. *Am J Orthod Dentofacial Orthop*. 2011;140(4):510-519. doi:10.1016/j.ajodo.2010.10.024

8. Cleall JF, Bayne DI, Posen JM, Subtelny JD. Expansion Of The Midpalatal Suture In The Monkey. *Angle Orthod*. July 2009. http://www.angle.org/doi/10.1043/0003-3219(1965)035%3C0023:EOTMSI%3E2.0.CO;2?url_ver=Z39.88-2003&rfr_id=ori:rid:crossref.org&rfr_dat=cr_pub%3Dpubmed. Accessed November 1, 2015.

9. McNamara JA, Lione R, Franchi L, et al. The role of rapid maxillary expansion in the promotion of oral and general health. *Prog Orthod*. 2015;16(1):33. doi:10.1186/s40510-015-0105-x

10. Obstructive Sleep Apnea Syndrome in Children. http://www.medscape.com/viewarticle/746822_8. Accessed October 31, 2015.

11. Fastuca R, Perinetti G, Zecca PA, Nucera R, Caprioglio A. Airway compartments volume and oxygen saturation changes after rapid maxillary expansion: A longitudinal correlation study. *Angle Orthod*. February 2015.

doi:10.2319/072014.1

12. Cordasco G, Nucera R, Fastuca R, et al. Effects of orthopedic maxillary expansion on nasal cavity size in growing subjects: A low dose computer tomography clinical trial. *Int J Pediatr Otorhinolaryngol*. 2012;76(11):1547-1551. doi:10.1016/j.ijporl.2012.07.008

13. Hershey HG, Stewart BL, Warren DW. Changes in nasal airway resistance associated with rapid maxillary expansion. *Am J Orthod*. 1976;69(3):274-284. doi:10.1016/0002-9416(76)90076-2

14. Görgülü S, Gokce SM, Olmez H, Sagdic D, Ors F. Nasal cavity volume changes after rapid maxillary expansion in adolescents evaluated with 3-dimensional simulation and modeling programs. *Am J Orthod Dentofac Orthop*. 2011;140(5):633-640. doi:10.1016/j.ajodo.2010.12.020

15. Warren DW, Hershey G, Turvey TA, Hinton VA, Hairfield WM. The nasal airway following maxillary expansion. *Am J Orthod Dentofac Orthop*. 1987;91(2):111-116. doi:10.1016/0889-5406(87)90467-7

16. Caprioglio A, Meneghel M, Fastuca R, Zecca PA, Nucera R, Nosetti L. Rapid maxillary expansion in growing patients: Correspondence between 3-dimensional airway changes and polysomnography. *Int J Pediatr Otorhinolaryngol*. 2014;78(1):23-27. doi:10.1016/j.ijporl.2013.10.011

17. Pirelli P, Saponara M, Guilleminault C. Rapid maxillary expansion (RME) for pediatric obstructive sleep apnea: a 12-year follow-up. *Sleep Med*. 2015;16(8):933-935. doi:10.1016/j.sleep.2015.04.012

18. Bouserhal J, Bassil-Nassif N, Tauk A, Will L, Limme M. Three-dimensional changes of the naso-maxillary complex following rapid maxillary expansion. *Angle Orthod*. 2014;84(1):88-95. doi:10.2319/011313-36.1

19. Farronato G, Giannini L, Galbiati G, Maspero C. RME: influences on the nasal septum. *Minerva Stomatol*. 2012;61(4):125-134. http://www.researchgate.net/publication/221970226_RME_influences_on_the_nasal_septum. Accessed November 2, 2015.

20. Altug-Atac AT, Atac MS, Kurt G, Karasud HA. Changes in nasal structures following orthopaedic and surgically assisted rapid maxillary expansion. *Int J Oral Maxillofac Surg*. 2010;39(2):129-135. doi:10.1016/j.ijom.2009.11.013

21. Miner RM, Al Qabandi S, Rigali PH, Will LA. Cone-beam computed tomography transverse analysis. Part I: Normative data. *Am J Orthod Dentofac Orthop*. 2012;142(3):300-307. doi:10.1016/j.ajodo.2012.04.014

22. Smith T, Ghoneima A, Stewart K, et al. Three-dimensional computed tomography analysis of airway volume changes after rapid maxillary expansion. *Am J Orthod Dentofac Orthop*. 2012;141:618-626.

doi:http://dx.doi.org/10.1016/j.ajodo.2011.12.017

23. Ribeiro ANC, De Paiva JB, Rino-Neto J, Illipronti-Filho E, Trivino T, Fantini SM. Upper airway expansion after rapid maxillary expansion evaluated with cone beam computed tomography. *Angle Orthod*. 2012;82(3). doi:10.2319/030411-157.1

24. Iwasaki T, Saitoh I, Takemoto Y, et al. Tongue posture improvement and pharyngeal airway enlargement as secondary effects of rapid maxillary expansion: A cone-beam computed tomography study. *Am J Orthod Dentofac Orthop*. 2013;143(2):235-245. doi:10.1016/j.ajodo.2012.09.014

25. Chang Y, Koenig LJ, Pruszynski JE, Bradley TG, Bosio JA, Liu DW. Dimensional changes of upper airway after rapid maxillary expansion: A prospective cone-beam computed tomography study. *Am J Orthod Dentofac Orthop*. 2013;143(4):462-470. doi:10.1016/j.ajodo.2012.11.019

26. Li L, Qi S, Wang H, Ren S, Ban J. [Cone-beam CT evaluation of nasomaxillary complex and upper airway following rapid maxillary expansion]. *Zhonghua Kou Qiang Yi Xue Za Zhi*. 2015;50(7):403-407.

27. El H, Palomo JM. Three-dimensional evaluation of upper airway following rapid maxillary expansion: a CBCT study. *Angle Orthod*. 2014;84(2):265-273. doi:10.2319/012313-71.1

28. Zeng J, Gao X. A prospective CBCT study of upper airway changes after rapid maxillary expansion. *Int J Pediatr Otorhinolaryngol*. 2013;77(11):1805-1810. doi:10.1016/j.ijporl.2013.07.028

29. Lin L, Ahn HW, Kim SJ, Moon SC, Kim SH, Nelson G. Tooth-borne vs bone-borne rapid maxillary expanders in late adolescence. *Angle Orthod*. 2015;85(2):253-262. doi:10.2319/030514-156.1

30. Pereira JS, Jacob HB, Locks A, Brunetto M, Ribeiro GLU. Evaluation of the rapid and slow maxillary expansion using cone-beam computed tomography: A randomized clinical trial. *Dental Press J Orthod*. 2017;22(2). doi:10.1590/2177-6709.22.2.061-068.oar

31. Izuka EN, Feres MFN, Pignatari SSN. Immediate impact of rapid maxillary expansion on upper airway dimensions and on the quality of life of mouth breathers. *Dental Press J Orthod*. 2015;20(3):43-49. doi:10.1590/2176-9451.20.3.043-049.oar

32. Almuzian M, Ju X, Almukhtar A, Ayoub A, Al-Muzian L, McDonald JP. Does rapid maxillary expansion affect nasopharyngeal airway? A prospective Cone Beam Computerised Tomography (CBCT) based study. *Surgeon*. 2018;16(1):1-11. doi:10.1016/j.surge.2015.12.006

33. Gurani SF, Di Carlo G, Cattaneo PM, Thorn JJ, Pinhol EM. Effect of Head and

Tongue Posture on the Pharyngeal Airway Dimensions and Morphology in Three-Dimensional Imaging: a Systematic Review. *J Oral Maxillofac Res*. 2016;7(1). doi:10.5037/jomr.2016.7101

34. Muto T, Takeda S, Kanazawa M, Yamazaki A, Fujiwara Y, Mizoguchi I. The effect of head posture on the pharyngeal airway space. *Int J Oral Maxillofac Surg*. 2002:579-583. doi:10.1054/ijom.2002.0279

35. Guijarro-Martínez R, Swennen GRJ. Cone-beam computerized tomography imaging and analysis of the upper airway: a systematic review of the literature. *Int J Oral Maxillofac Surg*. 2011;40(11):1227-1237. doi:10.1016/j.ijom.2011.06.017

36. Razi, Tamineh ;Niknami, Mahdi; Ghazani F. Relationship between Hounsfield Unit in CT Scan and Gray Scale in CBCT. *J Dent Res Dent Clin Dent Prospects.* 2014;8(2). doi:10.5681/joddd.2014.019

List of Journal Title Abbreviations

Am J Orthod..American Journal of Orthodontics

Am J Orthod Dentofac Orthop...

....American Journal of Orthodontics and Dentofacial Orthopedics

Angle Orthod .... Angle Orthodontist

APOS Trends Orthod... APOS Trends in Orthodontics

Dent Cosm ....Dental Cosmos

Dental Press J Orthod.. Dental Press Journal of Orthodontics

Int J Oral Maxillofac Surg ....International Journal of Oral and Maxillofacial Surgery

Int J Pediatr Otorhinolaryngol ....International Journal of Pediatric Otorhinolaryngology

J Dent Res Dent Clin Dent Prospects ....

....Journal of Dental Research, Dental Clinics, Dental Prospects

J Laryngol Otol ....Journal of Laryngology and Otology

Minerva Stomatol...Minerva Stomatologica

Prog Orthod..Progress in Orthodontics

Sleep Med .... Sleep Medicine

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